TWO ANTENNA, TWO PASS INTERFEROMETRIC SYNTHETIC APERTURE RADAR

This invention was developed under Contract DE-AC04-94AL85000 between Sandia

5   Corporation and the U.S. Department of Energy. The U.S. Government has certain rights in

this invention.

FIELD OF THE INVENTION

The invention relates generally to data collection for topographic modeling and, more

10   particularly, to two antenna, two pass interferometric synthetic aperture radar ("IFSAR").

BACKGROUND OF THE INVENTION

Interferometric synthetic aperture radar ("IFSAR") is a radar system used to obtain

target height information and form multi-dimensional maps of imaged areas. IFSAR utilizes

15   at least two (2) SAR images of the same scene, formed at slightly different elevation angles

relative to each other, to extract information about target heights. Such images can be

coherently combined to ascertain the topography of the imaged area and produce three-

dimensional maps of the imaged area.

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Currently, IFSAR utilizes two (2) principal operational modes. The first mode is two-antenna, one-pass IFSAR in which a single aircraft with two (2) antennas, displaced in a direction normal to the flight path of the aircraft, flies by the scene of interest once while collecting data. The second mode is one-antenna, two-pass IFSAR in which a single aircraft

5 with a single antenna flies by the scene of interest twice, along slightly offset flight paths, while collecting data.

Each of these IFSAR operation modes possesses strengths and weaknesses. The two-antenna, one-pass mode allows for precise knowledge of baseline length, but often limits that baseline length. Additionally, residual system noise manifests itself as uncertainty in the

10 topographic height estimates with lesser baseline lengths resulting in increased height-noise and limiting the effective topographic resolution. Because the one-antenna, two-pass mode allows a greater separation of the antennas, it allows a larger baseline, and thereby has a diminished sensitivity to system noise. Although it produces less height-noise, it suffers from imprecise knowledge of the baseline length (antenna separation) between passes, and

15 consequently does not provide accurate target height scaling. Conventional navigation instruments are inadequate in measuring aircraft flight paths with suitable precision. Although a two-antenna, two-pass IFSAR has the potential to provide both the scaling accuracy of the two-antenna, one-pass mode and the height-noise performance of the one-antenna, two-pass mode, it currently does not have precise knowledge of the baseline length

20 between passes.

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It is well-known by workers in the art that the uncertainty in the target height decreases as the antenna baselines increases. By decreasing the uncertainty in the target's height, the accuracy of the resulting digital elevation model improves. One alternative for increasing the antenna baseline length entails equipping a single aircraft with additional

5   antennas with suitable offsets to generate greater baselines.. This is expensive and complicates the engineering. Additionally, flexing of the aircraft structure during flight may also be severe enough to render unacceptable uncertainty in the larger baselines without somewhat expensive baseline measurement schemes or devices.

It is therefore desirable to provide a solution that avoids the weaknesses of the

10   aforementioned conventional IFSAR modes.

Exemplary embodiments of the invention permit data driven alignment of multiple independent passes, thereby providing the scaling accuracy of the two-antenna, one-pass mode and the height-noise performance of the one-antenna, two-pass mode. The antenna baseline between multiple flight passes can be accurately estimated from the data itself,

15   thereby reducing both height-noise and scaling error and allowing for more accurate information about target ground position locations and heights.

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BRIEF DESCRIPTION OF THE DRAWINGS

The above and further advantages of the invention may be better understood by referring to the following description in conjunction with the accompanying drawings in which corresponding numerals in the different figures refer to the corresponding parts, in

5   which:

FIGURE 1 diagrammatically illustrates exemplary flight passes for a two-antenna, two-pass IFSAR system in accordance with exemplary embodiments of the present invention;

FIGURE 1A displays a table of some exemplary parameters for a two-antenna, two-

10   pass IFSAR system in accordance with the present invention;

FIGURE 2 diagrammatically illustrates geometry for a two-antenna, one-pass IFSAR system in accordance with the known art;

FIGURE 3 diagrammatically illustrates geometry for a two-antenna, one-pass IFSAR system with a negative antenna angle in accordance with the known art;

15   FIGURE 4 diagrammatically illustrates geometry for a two-antenna, two-pass IFSAR system in accordance with exemplary embodiments of the present invention;

FIGURE 5 diagrammatically illustrates two antenna pairs and pertinent geometry for an IFSAR system in accordance with exemplary embodiments of the present invention;

FIGURE 6 diagrammatically illustrates a single antenna pair and pertinent geometry

20   for an IFSAR system in accordance with the known art;

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FIGURE 7 graphically illustrates RMS values for baseline uncertainty in accordance with exemplary embodiments of the present invention;

FIGURE 8 graphically illustrates RMS uncertainty values for a target's ground range position in accordance with exemplary embodiments of the present invention;

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FIGURE 9 graphically illustrates RMS uncertainty values for a target's height in accordance with exemplary embodiments of the present invention; and

FIGURE 10 diagrammatically illustrates an exemplary embodiment of an apparatus for implementing a two-antenna, two-pass IFSAR in accordance with the present invention.

DETAILED DESCRIPTION

While the making and using of various embodiments of the present invention are discussed herein in terms of two-antenna, two-pass interferometric synthetic aperture radar ("IFSAR"), it should be appreciated that the present invention provides many inventive

5   concepts that can be embodied in a wide variety of contexts. The specific embodiments discussed herein are merely illustrative of specific ways to make and use the invention, and are not meant to limit the scope of the invention.

The present invention provides a solution that enables data driven alignment of multiple independent passes, thereby providing the scaling accuracy of the two-antenna, one-

10   pass IFSAR mode and the height-noise performance of the one-antenna, two-pass IFSAR mode. The two-antenna, two-pass IFSAR mode presented herein can accurately estimate the antenna baseline between two (2) flight passes from the data itself and reduce height-noise and scaling error, allowing for more accurate information about target ground position locations and heights. The two-antenna, two-pass IFSAR mode presented herein can use the

15   data collected from each individual flight pass to estimate the antenna baseline length between the passes. True three-dimensional radar imaging from stand-off aircraft and satellite platforms can be obtained via multi-pass IFSAR which can allow for data collectiom from more than two (2) flight passes.

FIGURE 1 diagrammatically illustrates exemplary flight passes **1** and **2** for a two-

20   antenna (**20a** and **20b**), two-pass (**1** and **2**) IFSAR system in accordance with exemplary

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embodiments of the present invention. Aircraft **10**, carrying antennas **20a** and **20b** (alternatively denoted as antenna pair **20**), can perform flight passes **1** and **2** along flight trajectory **30** over scene of interest **40**. Any type platform can be used to carry the radar system. Each flight pass can be performed at a different range, such as **R1** and **R2**, from scene of interest **40**. In some embodiments, each flight pass, such as flights passes **1** and **2**, can possess a different elevation angle to scene of interest **40**. Flight passes **1** and **2** are separated by a distance of **B** meters, therefore **B** represents the antenna baseline length between antenna pair **20** during flight pass **1** and antenna pair **20** during flight pass **2**. In some embodiments, **B** may be on the order of tens of meters. In some embodiments, flight passes **1** and **2** are as close to parallel as possible (similar to the one-antenna, two-pass mode). However, since IFSAR has been shown to be possible with non-parallel flight paths, the data itself can also be used to calibrate the relative flight paths. Some exemplary parameters for a two-antenna, two-pass IFSAR system are given in the table of FIGURE 1A. Despite modern navigation equipment, the antenna baseline length between two (2) flight passes is generally unknown at an accuracy and precision required to produce accurate target ground range position and height information for the imaged scene. While IFSAR topography measurements may be calibrated using ground-truth measurements, opportunities to collect such ground-truth measurements are not always available. Consequently, the antenna baseline length between flight passes needs to be accurately estimated by alternate means to yield improved ground range position and height accuracies.

FIGURE 2 diagrammatically illustrates geometry for a two-antenna, one-pass IFSAR system in accordance with the known art. In FIGURE 2, the center of the scene is denoted as the scene's central reference point ("**CRP**"). In practice, distances (such as r_1 and r_2) between the target (such as target **45**) and antennas (such as antennas **20a** and **20b**) are very

5   large relative to the smaller antenna baseline lengths (such as **b**) and scene sizes (such as scene of interest **40**, FIGURE 1). Under these conditions, the equations for estimating the target's ground range position s_y and height s_z when antenna angle θ_L is positive are:

$$\hat{s}_y = s \cdot \sin(\psi_c) \cdot \left[1 - \left\{ \frac{s^2 + r_c^2 - r_1^2}{2sr_c} \right\}^2 \right]^{1/2} - \cos(\psi_c) \cdot \left[\frac{s^2 + r_c^2 - r_1^2}{2r_c} \right] \qquad (1)$$

and

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$$\hat{s}_z = \sin(\psi_c) \cdot \left[\frac{s^2 + r_c^2 - r_1^2}{2r_c} \right] + s \cdot \cos(\psi_c) \cdot \left[1 - \left\{ \frac{s^2 + r_c^2 - r_1^2}{2sr_c} \right\}^2 \right]^{1/2}, \qquad (2)$$

where ψ_c represents the grazing angle of the radar system, which is conventionally available from the navigational system on the aircraft. Ranges r_1 and r_c are also conventionally available from the navigational system, while distance s between the **CRP** and target **49** can be calculated from data conventionally available from the navigational

15   system as discussed below with reference to FIGURE 4.

Figure 3 displays the geometry for a two-antenna, one-pass IFSAR system when antenna angle θ_L is negative. Range r_2 and angle γ are conventionally available from the

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aircraft's navigational system and distance **s** between the **CRP** and target **49** can be calculated from data conventionally available from the navigational system. Using the law of cosines, ξ is related to target angle θ_T by $(\pi - \theta_T)$ in radians or $(180° - \theta_T)$ in degrees. Target angle θ_T can be calculated as shown below:

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$$\theta_T = \psi_c - \gamma \qquad (3)$$

Using these equations, the target's ground range position s_y and height s_z estimation equations when antenna angle θ_L is negative are:

$$\hat{s}_y = -s \cdot \sin(\psi_c) \cdot \left[1 - \left\{ \frac{s^2 + r_c^2 - r_2^2}{2sr_c} \right\}^2 \right]^{1/2} - \cos(\psi_c) \cdot \left[\frac{s^2 + r_c^2 - r_2^2}{2r_c} \right] \qquad (4)$$

and

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$$\hat{s}_z = \sin(\psi_c) \cdot \left[\frac{s^2 + r_c^2 - r_2^2}{2r_c} \right] - s \cdot \cos(\psi_c) \cdot \left[1 - \left\{ \frac{s^2 + r_c^2 - r_2^2}{2sr_c} \right\}^2 \right]^{1/2} . \qquad (5)$$

Equations 1 and 2 use range r_1 with range r_c, while equations 4 and 5 use range r_2 with range r_c due to the setup and geometry of the problem. The long range condition between the platform and the scene, the small scene size, and the small baseline length condition between the two (2) individual antennas are all valid, making range r_1

15 approximately equal to range r_2, both of which are conventionally available from the aircraft's navigational system. Consequently, equations 1 and 2 can be interchanged with

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equations 4 and 5. The explicit derivations for these equations are well known to workers in the art.

FIGURE 4 diagrammatically illustrates geometry for a two-antenna, two-pass IFSAR system in accordance with exemplary embodiments of the present invention. Antennas **11** and **12** comprise an antenna pair (alternatively designated as **100**) for a first flight pass and are separated by a distance of b_1 meters. Antennas **21** and **22** comprise an antenna pair (alternatively designated as **200**) for a second flight pass and are separated by a distance of b_2 meters. The distances separating the antennas in each pair (i.e., b_1 and b_2) may differ and may be on the order of submeters (e.g., 0.3 meters).

Since it is conventionally known that the root mean square ("RMS") error associated with a target's ground range position and height estimates are inversely proportional to the antenna baseline length, it follows that a larger baseline length will yield smaller errors for these estimates. Consequently, by utilizing the antenna baseline length **B** between two (2) passes rather than the antenna baseline length (i.e., b_1 or b_2) between two (2) antennas of a single pass (see FIGURE 4) in conjunction with information from the flight passes, target ground range position s_y and height s_z scaling accuracies can be improved to the equivalent of the two-antenna, one-pass IFSAR system while retaining the height-noise performance associated with the one-antenna, two-pass IFSAR system. For a two-antenna, two-pass mode, midpoint **Mid₁** between antennas **11** and **12** and midpoint **Mid₂** between antennas **21** and **22** can be utilized as shown in FIGURE 4. The equations below can calculate an

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estimate of the antenna baseline length **B** between midpoint $\mathbf{Mid_1}$ of antenna pair **100** and midpoint $\mathbf{Mid_2}$ of antenna pair **200**. The distance from the scene's **CRP** to target **45** itself is:

$$s = \sqrt{s_y^2 + s_z^2} \quad . \tag{6}$$

Using conventional trigonometric equations and identities with the recorded phase (ψ_{c1} and ψ_{c2}) measurements, the ground range position and height of $\mathbf{Mid_1}$ are:

$$s_{y_1} = r_{c_1} \cdot \cos(\psi_{c_1}) \tag{7}$$

and

$$s_{z_1} = r_{c_1} \cdot \sin(\psi_{c_1}) \quad . \tag{8}$$

Similarly, the ground range position and height of $\mathbf{Mid_2}$ are:

$$s_{y_2} = r_{c_2} \cdot \cos(\psi_{c_2}) \tag{9}$$

and

$$s_{z_2} = r_{c_2} \cdot \sin(\psi_{c_2}) \quad . \tag{10}$$

The range (r_{c1} and r_{c2}) and phase (ψ_{c1} and ψ_{c2}) measurements are conventionally available from the aircraft's navigational system.

Using these two coordinate pairs, the estimation equation for antenna baseline length **B** between the two (2) flight passes is:

$$\hat{B} = \sqrt{(s_{z_1} - s_{z_2})^2 + (s_{y_1} - s_{y_2})^2} \quad . \tag{11}$$

This result can be used to re-estimate the target's ground range position s_y and height s_z for a two-antenna, two-pass IFSAR system, resulting in refined estimates of the target's

ground range position s_y and height s_z. When using multiple targets to calculate the antenna baseline estimate, equations 7-11 can be calculated for each of the targets and the resulting baseline estimates averaged to obtain $\hat{B}$. FIGURE 5 is similar to FIGURE 4 and diagrammatically illustrates two antenna pairs (antennas **11** and **12**, alternatively designated as antenna pair **100**, and antennas **21** and **22**, alternatively designated as antenna pair **200**) and pertinent geometry for an IFSAR system in accordance with exemplary embodiments of the present invention. Using antenna baseline length $\hat{B}$ between the two (2) flight passes (equation 11), the equation for antenna angle θ_L becomes:

$$\theta_L = \sin^{-1}\left(\frac{\hat{B}}{2r_2} + \frac{\lambda(\phi + 2\pi \cdot m)}{4\pi \hat{B}} - \frac{\lambda^2(\phi + 2\pi \cdot m)^2}{32\pi^2 \hat{B} r_2} \right). \qquad (12)$$

This equation can account for phase ambiguities where the variable 'm' represents the integer ambiguity index. As conventionally known, there are ambiguities in the phase due to the fact that the phase is equivalent every 2π radians. The possible values of 'm' are bounded by the navigational system and can be generated as conventionally known to workers in the art. In some embodiments, equation 12 can be calculated once for each 'm' value. Also, λ is the system wavelength (e.g., 0.02 meters as in FIGURE 1A), and ϕ is the phase difference conventionally calculated as the difference in the range times the constant $2\pi/\lambda$ (i.e., $\phi = (2\pi/\lambda) * (r_2 - r_1)$).

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If equation 12 yields a positive antenna angle θ_L, and noting that ranges r_2 and r_c are conventionally available from the aircraft's navigational system while distance s from the scene's **CRP** to target **45** can be calculated from data conventionally available from the navigational system, the following refined estimation equations apply:

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$$\hat{s}_y = s \cdot \sin(\psi_c) \cdot \left[1 - \left\{ \frac{s^2 + r_c^2 - r_2^2}{2sr_c} \right\}^2 \right]^{1/2} - \cos(\psi_c) \cdot \left[\frac{s^2 + r_c^2 - r_2^2}{2r_c} \right] \qquad (13)$$

$$\hat{s}_z = \sin(\psi_c) \cdot \left[\frac{s^2 + r_c^2 - r_2^2}{2r_c} \right] + s \cdot \cos(\psi_c) \cdot \left[1 - \left\{ \frac{s^2 + r_c^2 - r_2^2}{2sr_c} \right\}^2 \right]^{1/2} \qquad (14)$$

If antenna angle θ_L is negative in equation 12, the appropriate refined estimation equations become:

$$\hat{s}_y = - s \cdot \sin(\psi_c) \cdot \left[1 - \left\{ \frac{s^2 + r_c^2 - r_2^2}{2sr_c} \right\}^2 \right]^{1/2} - \cos(\psi_c) \cdot \left[\frac{s^2 + r_c^2 - r_2^2}{2r_c} \right] \qquad (15)$$

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$$\hat{s}_z = \sin(\psi_c) \cdot \left[\frac{s^2 + r_c^2 - r_2^2}{2r_c} \right] - s \cdot \cos(\psi_c) \cdot \left[1 - \left\{ \frac{s^2 + r_c^2 - r_2^2}{2sr_c} \right\}^2 \right]^{1/2} \qquad (16)$$

Equations 13 and 14 are similar to equations 1 and 2, but use range r_2 rather than range r_1, while equations 15 and 16 are the same as equations 4 and 5 (all use range r_2). As discussed above with reference to equations 1, 2, 4, and 5, the long range condition between the platform and the scene, the small scene size, and the small baseline length condition

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between the two (2) individual antennas are all valid, making range r_1 approximately equal

to range r_2. Also in equations 13-16, r_c can be either r_{c1} or r_{c2} with its corresponding ψ_c

value (ψ_{c1} or ψ_{c2}, respectively). (It is r_{c2} and ψ_{c2} in FIGURE 10 described below.)

FIGURE 10 diagrammatically illustrates exemplary embodiments of an apparatus for

5   implementing a two-antenna, two-pass IFSAR in accordance with the present invention. The

aircraft's navigational system **1005** can supply ranges r_1, r_2, r_{c1} and r_{c2}, phase measurements

ψ_{c1} and ψ_{c2}, target ground range s_y, target height s_z, and system wavelength λ. With r_{c1}, r_{c2},

ψ_{c1}, and ψ_{c2} as inputs, ground range estimator **1010** implements equations 7 and 9,

outputting ground range estimates s_{y1} and s_{y2}, and height estimator **1015** implements

10   equations 8 and 10, outputting height estimates s_{z1} and s_{z2}. Baseline estimator **1020** receives

the outputs of ground range estimator **1010** and height estimator **1015** and, implementing

equation 11, produces antenna baseline estimate $\hat{B}$ which is input to antenna angle estimator

1030. With ψ_{c1} and ψ_{c2} as inputs, 'm' generator **1040** generates a range of 'm' values which

are input to antenna angle estimator **1030**. Phase difference estimator **1025** receives ranges

15   r_1 and r_2 and system wavelength λ from navigational system **1005**. Phase difference

estimator **1025** implements the equation $((2\pi/\lambda) * (r_2 - r_1))$ to produce ϕ which is input to

antenna angle estimator **1030**. Using $\hat{B}$, **m**, and ϕ along with λ and r_2 from navigational

system **1005**, antenna angle estimator **1030** implements equation 12 and produces an

estimate of antenna angle θ_L. Selector **1035** receives from antenna angle estimator **1030** a

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positive/negative indication for θ_L. Based on the sign of θ_L, selector **1035** will select either ground range and height estimator **1045** or ground range and height estimator **1050**. Ground range and height estimator **1045** implements equations 15 and 16 for a negative θ_L and ground range and height estimator **1050** implements equations 13 and 14 for a positive θ_L.

5   Reference distance estimator **1055** receives s_y and s_z from navigational system **1005**, implements equation 6, and produces distance **s** (the distance from the scene's central reference point to the target) which is input to both ground range and height estimators **1045** and **1050**. In the exemplary embodiments of FIGURE 10, both ground range and height estimators **1045** and **1050** receive ranges r_2, r_{c2}, and phase measurement ψ_{c2} from

10   navigational system **1005** and distance **s** from reference distance estimator **1055** for use in producing refined ground range and height estimations $\hat{s}_y$ and $\hat{s}_z$.

The uncertainties in a target's ground range position and height estimates for a two-antenna, one-pass IFSAR system in the presence of noise can be derived with reference to FIGURE 6 wherein antennas **20a** and **20b** (i.e., a single antenna pair) are located on the

15   order of kilometers away from a scene of interest that includes central reference point **CRP**. These uncertainties are known to workers in the art. In FIGURE 6, the scene size is small compared to range r_c, and height s_z from the ground to target **45** on a first order approximation is equal to:

$$s_z \approx r_c \cdot \theta_L \cdot \cos(\psi_c). \tag{17}$$

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Here, grazing angle ψ_c is constant and antenna angle θ_L varies. Under small scene

size and long range constraints, point $\mathbf{P_1}$ is approximately the same distance from the radar

platform as the **CRP** on a first order basis. Therefore, the distance between **CRP** and $\mathbf{P_1}$ is

very small in comparison to range $\mathbf{r_c}$. Under small antenna angle conditions and using first

5   order partial derivative concepts as known in the art, the uncertainties in target **45** ground

range position $\mathbf{s_y}$ and height $\mathbf{s_z}$ for a two-antenna, one-pass IFSAR system reduce to the

following well known approximations:

$$\sigma_{s_y}^2 \approx \frac{\lambda^2 \cdot r_c^2 \cdot \sin^2(\psi_c)}{16b^2\pi^2 \cdot \text{SNR}} \tag{18}$$

and

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$$\sigma_{s_z}^2 \approx \frac{\lambda^2 \cdot r_c^2 \cdot \cos^2(\psi_c)}{16b^2\pi^2 \cdot \text{SNR}}, \tag{19}$$

respectively, where, as known by workers in the art, the phase variance is related to

the signal to noise ratio ("SNR") as:

$$\sigma_\phi^2 = \frac{1}{\text{SNR}}. \tag{20}$$

The uncertainties in a target's ground range position $\mathbf{s_y}$ and height $\mathbf{s_z}$ estimates for

15   exemplary embodiments of a two-antenna, two-pass IFSAR system in the presence of noise

can be derived with reference to FIGURE 4. Using the antenna baseline length estimation

equation (Equation 11), the uncertainty in antenna baseline length **B** can be calculated in

terms of the uncertainty in the difference between the antenna pairs' midpoint (**Mid₁** and

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Mid$_2$) height coordinates (i.e., the difference $s_{z1} - s_{z2}$) and the uncertainty in the difference

between the ground range coordinates for these two midpoints (i.e., the difference $s_{y1} - s_{y2}$).

The overall antenna baseline uncertainty with respect to the uncertainties in both of these two

(2) differences is:

$$\sigma_B^2 = [\,\sigma_B^2 \mid \sigma^2_{(s_{y1}-s_{y2})}\,] + [\,\sigma_B^2 \mid \sigma^2_{(s_{z1}-s_{z2})}\,] . \tag{21}$$

After computing the two (2) individual components in the antenna baseline length

uncertainty, the uncertainty in grazing angle ψ_{c1} can be utilized to obtain the final baseline

uncertainty equation. Using the geometry in Figure 4, this overall uncertainty becomes:

$$\sigma_B^2 = \frac{1}{s^2 \cdot M \cdot SNR} \cdot \left\{ (r_{c_1} - r_{c_2})^2 \cdot \cos^2(\psi_{c_1}) \right\} \cdot$$

$$\left\{ \frac{r_I^2 \cdot \lambda^2 \cdot \cos^2(\psi_{c_2})}{16\pi^2 \cdot b_2^{\,2}} + \frac{r_I^2 \cdot \lambda^2}{32\pi^2 \left(r_{c_1}^2 - \dfrac{(r_{c_1}^2 + s^2 - r_I^2)^2}{4s^2} \right)} + \right.$$

$$\left. + \frac{(-s^2 + r_{c_1}^2 - r_I^2)^2 \cdot r_I^2 \cdot \lambda^2}{16\pi^2 \cdot b_2^{\,2} \cdot (2r_I^2(s^2 + r_{c_1}^2) - (s^2 - r_{c_1}^2)^2 - r_I^4)} \right\} \tag{22}$$

This equation assumes the use of M independent targets to calculate the antenna

baseline length estimate. That is, in some embodiments, baseline estimator **1020** of FIGURE

10 can implement equations 7-11 for each of M targets and then average the M results to

obtain its output baseline length estimate $\hat{B}$. The baseline uncertainty in terms of the RMS

from a single target's measurements is shown in Figure 7. The RMS for the antenna baseline

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length uncertainty is plotted as a function of SNR and the distance from the target to the scene's **CRP**.

Two observations can be made from the baseline standard deviation presented in Figure 7. First, as the SNR increases, the standard deviation of the baseline length estimate decreases because as the signal power increases relative to the noise power, the overall SNR increases. As signal noise decreases, the uncertainties in estimating the antenna baseline, the target location, and the target height also decrease. The second observation is that as the target moves farther away from the scene's **CRP** (i.e., the distance from the scene's **CRP** increases), the uncertainty in the baseline length estimate decreases because the baseline length uncertainty is inversely proportional to the target's distance from the scene's **CRP**. As the distance increases, the baseline length uncertainty will converge to zero since the first term in the brackets in Equation 22 will dominate the other two terms. From these two observations, if can be inferred that the exemplary conditions for accurately estimating the antenna baseline length between the two antenna pairs is to utilize a high SNR with targets located as far away as possible from the scene's **CRP** within the scene of interest. In other words, large target swaths are better for estimating baseline lengths than narrow target swaths.

In a two-antenna, two-pass IFSAR system, the refined estimates of target ground range position s_y and height s_z estimates also possess uncertainties. These uncertainties, respectively, are:

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$$\sigma_{s_y}^2 = (r_c \cdot \sin(\psi_c))^2 \cdot \sigma_{\theta_L}^2 \tag{23}$$

and

$$\sigma_{s_z}^2 = (r_c \cdot \cos(\psi_c))^2 \cdot \sigma_{\theta_L}^2 . \tag{24}$$

Using the antenna baseline length **B** between the two antenna pairs (such as **100** and **200**), the uncertainty in the antenna angle θ_L becomes:

$$\sigma_{\theta_L}^2 = \frac{1}{SNR} \cdot \left(\frac{\lambda}{4\pi B} - \frac{\lambda^2 \phi}{16\pi^2 B r_2} \right)^2 + \left(\frac{1}{2r_2} - \frac{\lambda \phi}{4\pi B^2} + \frac{\lambda^2 \phi^2}{32\pi^2 B^2 r_2} \right)^2 \cdot \sigma_B^2 . \tag{25}$$

It is evident from the above three equations that as the antenna baseline length estimation uncertainty increases, the uncertainties in both the target ground range position s_y and height s_z also increase. Utilizing the uncertainty in antenna angle θ_L in Equation 25 with the uncertainty in the antenna baseline length **B** in Equation 22, the uncertainty in estimating the target's refined ground range position s_y is:

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$$\sigma_{s_y}^2 = \frac{1}{SNR} \cdot \left\{ \left(\frac{\lambda}{4\pi B} - \frac{\lambda^2 \phi}{16\pi^2 B r_2} \right)^2 \cdot \left(r_c \cdot \sin(\psi_c) \right)^2 \right\} +$$

$$\frac{1}{s^2 \cdot M \cdot SNR} \cdot \left\{ \begin{array}{l} \left(r_c \cdot \sin(\psi_c) \right)^2 \cdot \left(\left(r_{c_1} - r_{c_2} \right)^2 \cdot \cos^2(\psi_{c_1}) \right) \cdot \\ \left(\frac{1}{2r_2} - \frac{\lambda \phi}{4\pi B^2} + \frac{\lambda^2 \phi^2}{32\pi^2 B^2 r_2} \right)^2 \cdot \\ \left[\frac{r_1^2 \cdot \lambda^2 \cdot \cos^2(\psi_{c_2})}{16\pi^2 \cdot b^2} + \frac{r_1^2 \cdot \lambda^2}{32\pi^2 \left(r_{c_1}^2 - \frac{(r_{c_1}^2 + s^2 - r_1^2)^2}{4s^2} \right)} + \right. \\ \left. \frac{(-s^2 + r_{c_1}^2 - r_1^2)^2 \cdot r_1^2 \cdot \lambda^2}{16\pi^2 \cdot b^2 \cdot (2r_1^2(s^2 + r_{c_1}^2) - (s^2 - r_{c_1}^2)^2 - r_1^4)} \right] \end{array} \right\}$$

$$(26)$$

where M targets are used to estimate the antenna baseline length **B** between two antenna pairs (such as **100** and **200**). On a first order approximation, the uncertainty in the target ground range position s_y with respect to the antenna baseline length **B** between two antenna pairs (such as **100** and **200**) becomes the well known expression:

$$\sigma_{s_y}^2 = \frac{\lambda^2 \cdot r_c^2 \cdot \sin^2(\psi_c)}{16\pi^2 \cdot SNR \cdot B^2} \cdot \tag{27}$$

Figure 8 displays the RMS values for the target's refined ground range position s_y error uncertainty. In this figure, as the SNR increases, the RMS values in the uncertainty

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decrease. This is also true for the target's distance from the scene's **CRP**. Targets located

farther away from the scene's **CRP** within the scene of interest possess smaller RMS values

in the ground range position s_y uncertainties than targets located closer to the scene's **CRP**.

As seen from the first order approximation, the ground range position s_y uncertainty will

5   converge to the value in Equation 27.

Using M targets to estimate the antenna baseline length **B** between two antenna pairs

(such as **100** and **200**), the uncertainty in the target's refined height s_z estimate is:

$$\sigma_{s_z}^2 = \frac{1}{SNR} \cdot \left\{ \left(\frac{\lambda}{4\pi B} - \frac{\lambda^2 \phi}{16\pi^2 B r_2} \right)^2 \cdot (r_c \cdot \cos(\psi_c))^2 \right\} +$$

$$\frac{1}{s^2 \cdot M \cdot SNR} \cdot \left\{ \begin{array}{l} (r_c \cdot \cos(\psi_c))^2 \cdot \left((r_{c_1} - r_{c_2})^2 \cdot \cos^2(\psi_{c_1}) \right) \cdot \\[2mm] \left(\frac{1}{2r_2} - \frac{\lambda \phi}{4\pi B^2} + \frac{\lambda^2 \phi^2}{32\pi^2 B^2 r_2} \right)^2 \cdot \\[3mm] \left\{ \frac{r_1^2 \cdot \lambda^2 \cdot \cos^2(\psi_{c_2})}{16\pi^2 \cdot b^2} + \frac{r_1^2 \cdot \lambda^2}{32\pi^2 \left(r_{c_1}^2 - \frac{(r_{c_1}^2 + s^2 - r_1^2)^2}{4s^2} \right)} \div \right. \\[5mm] \frac{(-s^2 + r_{c_1}^2 - r_1^2)^2 \cdot r_1^2 \cdot \lambda^2}{16\pi^2 \cdot b^2 \cdot (2r_1^2(s^2 + r_{c_1}^2) - (s^2 - r_{c_1}^2)^2 - r_1^4)} \end{array} \right\}$$

(28)

On a first order approximation, the uncertainty in the target height s_z with respect to the antenna baseline length **B** between two antenna pairs (such as **100** and **200**) becomes the well known expression:

$$\sigma^2_{s_z} = \frac{\lambda^2 \cdot r_c^2 \cdot \cos^2(\psi_c)}{16\pi^2 \cdot SNR \cdot B^2} \cdot \qquad (29)$$

5   It can therefore be inferred that in order to decrease the uncertainty in the target height s_z, bigger antenna baselines **B** are necessary. Similar to the ground range position s_y uncertainty, the target height s_z uncertainty converges to the first order approximation shown in Equation 29.

Figure 9 displays the RMS uncertainty values for estimating the target's refined

10   height s_z in terms of the SNR and the target's distance from the scene's **CRP**. Similar to the observations from the target's refined ground range position s_y estimation procedure, the RMS uncertainty values for the refined height s_z estimates decrease as the SNR is increased and as the target moves farther away from the scene's **CRP** within the scene of interest.

It will be evident to workers in the art that the exemplary embodiments described

15   above can be readily implemented by suitable modifications in software, hardware or a combination of software and hardware in conventional topographic modeling systems, such as IFSAR systems.

Although exemplary embodiments of the present invention have been described in detail, it will be understood by workers in the art that various modifications can be made

therein without departing from the spirit and scope of the invention as set forth in the appended claims.